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SUMMARY

A monocoque box specimen of aluminum alloy was subjected to end compression and the strains in the stringers were measured up to loads at which permanent set became noticeable. The stringer strains at low loads agreed closely with those computed from the assumption of uniform stress distribution. Buckling of the 0.026-inch sheet between stringers and of the 0.075-inch shear web took place at stresses in accord with theoretical values. Permanent set became noticeable at a load of 115,200 pounds, corresponding to an average stringer stress of about 16,000 pounds per square inch. The measured average strain above the first buckling load was within 2 percent of the theoretical strain as calculated from the dimensions of the box and effective width formulas due to Marguerre and to Cox.

INTRODUCTION

Compressive tests of a monocoque box specimen were made as part of an investigation on monocoque boxes for the National Advisory Committee for Aeronautics. The investigation was authorized in July 1937 for the purpose of studying the stress distribution and the deformation under a number of different loading conditions of a monocoque box beam having dimensions within the range encountered in design.

Originally it was planned to test at least three boxes: the first one with greater reinforcement than customary in design, the second with a representative amount of reinforcement, and the third with less than representative reinforcement. The program was restricted to a single box of representative design when it was found that the cost of the specimens would be comparable with the cost of the entire test program.

It was decided to begin with compressive tests and to follow with tests under transverse loads and possibly with tests under torsional loads.

The compressive tests were designed to give information on the following points:

1. Adequacy of the loading fixtures in producing an approximately uniform strain distribution over the cross section of the specimen.

2. Operation of special strain-gage equipment for measuring stringer strains.

3. Maximum stress supported by specimen without appreciable permanent damage.

4. Comparison of load-compression curve with that calculated from the dimensions of the box and the results of panel tests previously made at this Bureau (reference 1).

SPECIMEN

The over-all dimensions and the design of the monocoque box specimen are given in figure 1. The box was fabricated from 24ST aluminum alloy; 0.075-inch sheet was used for the shear web sides, and 0.026-inch sheet reinforced by Z-stringers spaced 4 inches on centers was used for the top and the bottom faces of the box. The stringers were fastened to the sheet by 1/8-inch brazier-head rivets, spaced 7/8 inch on centers. The top and the bottom faces of the box were nominally of the same design as end compression panel 6 described in reference 1.

The cross-sectional area of the sheet material in the box was estimated as

$$A_s = 2.12 \text{ square inches}$$

that of the ten stringers, as

$$A_{st} = 1.33 \text{ square inches}$$

and that of the four corner posts as

$$A_c = 5.01 \text{ square inches}$$

giving a total area

$$A = A_s + A_{st} + A_c = 8.46 \text{ square inches}$$

The ratio of area of reinforcement to total area was

$$\frac{A_{st} + A_c}{A} = 0.750$$

Particular care was taken in reinforcing the ends of the box to avoid concentration of the compressive and the flexural loads on particular portions of the box. The reinforcements, consisting of steel angles and plates, are shown in figures 1, 2, and 3. Figure 3 also shows the construction of the bulkheads.

Tensile and compressive stress-strain curves of material from the corner posts, the stringers, and the sheet used in assembling the monocoque box are shown in figures 4 and 5. The compressive properties of the corner posts and the stringers were obtained from compressive tests on 4-inch lengths of these members. The compressive properties of the sheet were obtained from pack tests (reference 2). Young's modulus and the yield strength obtained from the stress-strain curves are listed in table I. The properties of the material appear to be typical of 24ST aluminum alloy.

TEST PROCEDURE

Figure 6 shows the monocoque box specimen mounted for a compressive test between the heads of a hydraulic testing machine of 2,300,000-pound capacity. The following procedure was used in mounting the specimen. A sealing strip of 1-inch sponge rubber was glued on the end plates A of the box to provide the necessary space for a layer of plaster of paris. The heads of the testing machine were greased and covered with a layer of aluminum foil to prevent corrosive action of the plaster of paris on the heads. The specimen was centered relative to the heads and a sufficient load (about 200 pounds) was applied to reduce the thickness of the sponge-rubber seal to one-half inch. Plaster of paris mixed with a retarding agent was poured in at one end and was allowed to harden under load for 1 day. The sealing strips were removed and the procedure was repeated to cast a 1/2-inch layer of plaster of paris on the other end of the specimen.

The uniformity of load distribution over the section of the specimen was checked by 16 Tuckerman optical strain gages, which were attached to the stringers and the corner posts of the specimen as shown in figures 6 and 7. The strains in the four corner posts were measured over 10-inch gage lengths with 2-inch Tuckerman strain gages having an 8-inch extension. The average strain in each one of the five stringers on the "bottom" face of the specimen was measured with a pair of 2-inch Tuckerman strain gages. One gage of each pair was mounted directly on the outer flange of the stringer; the other gage had its gage points connected to the inner flange of the stringer by a special transfer of the lever type to be described later. The gages on the outer flange were held in place by C-springs acting on the top of the gage and the under side of the stringer flange. The lever transfers were held against the stringers by leaf springs of aluminum-alloy sheet which were, in turn, connected to the supporting channel C (fig. 7). The lever-and-gage combination was suspended at its center of gravity by a thread attached to channel C. Channel C was connected to the corner posts of the specimen by a flexible mounting to prevent any appreciable stiffening of the specimen by the channel. One pair of Tuckerman strain gages was attached in the same manner to the middle stringer on the "top" face of the box.

The lever-type transfer, which was designed for these tests, is shown in figure 8 together with a 2-inch Tuckerman strain gage. The transfer was made from a 2 3/8- by 1 1/4- by 5/16-inch block of tool steel by drilling two 3.1-millimeter holes at B and C, with a thickness of metal of 0.008 inch between the holes, and then cutting diagonal slots, as shown, from the long sides of the block to the holes. Sixty-degree gage points were inserted at D and F, 2 inches apart. The weight of the transfer was reduced by drilling lightening holes A.

Seven transfers of this construction were built and each one of them was calibrated by applying a known relative displacement up to 0.010 inch to the points D and F and measuring the relative displacement between E and G indicated by a 2-inch Tuckerman strain gage mounted on the transfer. The ratio of the two displacements ranged from 0.942 to 0.994.

The transfer just described should not be confused with the parallel-motion transfer of the Meisse type (reference 3), of which several have also been constructed at the National Bureau of Standards. Unfortunately, only three Meisse transfers were available, and time did not permit the construction of a sufficient number of additional transfers for these tests. The Meisse transfer has a wider field of application than the lever-type transfer and the only reason for using the lever-type one was that it could be constructed much more quickly and cheaply and that it was satisfactory for the application at hand.

The uniformity of load distribution near one end of the box and the operation of the strain-gage equipment were checked by mounting 12 gages on the bottom side and four on the top side at a section about 27 inches from that end of the box (fig. 6) and observing the changes in strain corresponding to changes in load from 0 to 8,800 pounds. The measurements were repeated with 12 gages on the top side and 4 on the bottom side for a section about 27 inches from the other end of the box. The strains indicated by the gages were equal within the error of measurement to the average strain computed from the load, the cross-sectional area, and Young's modulus in compression of the material ($E = 10.8 \times 10^6$ pounds per square inch). It was concluded that the method of mounting strain gages and of applying the load was satisfactory and the compressive tests were proceeded with.

The compressive tests were made with all 16 strain gages mounted near the midsection of the specimen (fig. 9). Strains were read for load increments of about 5,000 pounds, and the load was brought back repeatedly to a low value for reading of permanent set.

The bowing normal to the sheet of the center stringer between two bulkheads on both the top and the bottom faces of the box was measured with a dial gage mounted on a portable frame. Such measurements seemed desirable to detect any noticeable distortion of the section as a whole. The buckling of the sheet between stringers and of the shear web was observed visually by suitable illumination. (See, for instance, fig. 10, showing buckling of the sheet between stringers.)

RESULTS

The measured stringer strains and the strains in the four corner posts are plotted for each load in figure 11. Deviations from a uniform strain distribution became noticeable at a load of 20,000 pounds and they increased with load until a maximum deviation of about 10 percent was reached at the highest load applied, 115,200 pounds. The difference between extreme fiber strains and the average strain in any stringer attained 4 percent of the average strain in the stringer. The sign of the difference is seen to alternate from stringer to stringer. This result suggests a connection with the buckles in the sheet between stringers. The buckles had a symmetrical pattern (figs. 9 and 10) continuing across the stringers so that a crest in one sheet bay corresponded to a trough in the adjacent bay and vice versa. The twisting moments acting on the stringers due to these buckles may set up secondary bending strains with alternating sign on adjacent stringers because of the restraint of the stringers by the rivet line.

The average strain in each stringer and the strain in each of the four corner posts are plotted in figure 12 as circles and squares, respectively. The average strain for the entire section was obtained from these strains by multiplying each strain by the cross-sectional area of the structural element on which the strain gages were mounted, adding, and dividing the sum by the total area of the elements. This average strain is shown by crosses in figure 12. The individual strains are within 10 percent of the average strain in all cases. Figure 12 also shows the permanent set indicated by the strain gages when the load was reduced to a low value. This permanent set was consistently positive at a load of 115,200 pounds. The test was not carried beyond this load in order to leave the box undamaged for the tests under other types of loading. The average stringer stress at a load of 115,200 pounds was about 16,000 pounds per square inch.

Buckling of the sheet between stringers was observed at a load of about 21,000 pounds, at which the average stringer stress was about 2,500 pounds per square inch. This result agrees with the buckling stress of 2,500 pounds per square inch found for the sheet-stringer panel of the same design tested previously at this Bureau (reference 1, p. 42). The theoretical buckling stress for rigid clamping at the stringer was found to be $\sigma_{cr} = 2,880$ pounds per square inch (reference 4, p. 345). The wave length of the buckles was about 4.8 inches, in close agreement with the wave length of 4.7 inches observed in panel 6 of reference 1.

Buckling of the 0.075-inch shear web forming the sides of the box was too gradual for visual observation of the critical load. Deflection measurements at the center of the web between web stiffeners indicated a rapid increase in deflection beginning at a load of 70,000 pounds. This value corresponded to an average stress of about 8,800 pounds per square inch in the corner posts to which the web was riveted. This result agrees with the theoretical buckling stress of 8,800 pounds per square inch which was derived from Timoshenko's theory (reference 4) for a plate having the dimensions of the shear web between bulkheads (length = bulkhead spacing = 8.5 inches, width = 6.6 inches, thickness = 0.075 inch) rigidly clamped along the edges parallel to the load and simply supported along the loaded edges.

The bowing of the middle stringer normal to the sheet was in every case too small to be measured (less than 0.002 inch between bulkheads).

The curves shown in figure 12 give relations between total load and average compressive strain calculated as follows. The total load was divided into three parts, the load P_1 carried by the reinforcements, the load P_2 carried by the 0.026-inch sheet between stringers, and the load P_3 carried by the 0.075-inch shear web. The load P_1 was calculated upon the assumption of simple compression:

$$P_1 = A_1 E\epsilon = (A_c + A_{st})E\epsilon = 6.33 \times 1.08 \quad 10^7 \epsilon = 6840 \; (10^4 \epsilon) \qquad (1)$$

The loads P_2 and P_3 were calculated from

$$\left.\begin{aligned} P_2 &= A_2 E\epsilon \frac{w}{b} = 1.11 \quad 1.08 \quad 10^7 \epsilon \frac{w}{b} = 1200(10^4 \epsilon) \frac{w}{b} \\ P_3 &= A_3 E\epsilon \frac{w}{b} = 1.01 \quad 1.08 \quad 10^7 \epsilon \frac{w}{b} = 1090(10^4 \epsilon) \frac{w}{b} \end{aligned}\right\} \text{---} \; (2)$$

where w/b is the ratio of effective width of sheet to initial width. This ratio is unity below the buckling load of the sheet. Its value above the buckling load was calculated from two formulas, both of which had given good agreement with the observed effective width for the panels described in reference 1. Curve A of figure 12 was computed from Marguerre's formula for a sheet of thickness t with simply supported edges (reference 1, p. 45):

$$\frac{w}{b} = 1.54 \left(\frac{t}{b}\right)^{2/3} \epsilon^{-1/3} \qquad (3)$$

and curve B was calculated from Cox's formula for a sheet whose buckling stress σ_{cr} is known (reference 1, p. 44):

$$\frac{w}{b} = 0.14 + 0.85 \sqrt{\frac{\epsilon_{cr}}{\epsilon}} \qquad \epsilon_{cr} = \frac{\sigma_{cr}}{E} \qquad (4)$$

The buckling stress σ_{cr} in (4) was taken as the theoretical value for rigid clamping on the edges parallel to the load, which, as already mentioned, agreed satisfactorily with the observed buckling stress, i.e.:

σ_{cr} = 2,880 pounds per square inch for the sheet between stringers

σ_{cr} = 8,800 pounds per square inch for the shear web

Substitution of these values in (4) and the ratios

$t/b = 0.026/4 = 0.0065$ for the sheet between stringers

$t/b = 0.075/6.6 = 0.0114$ for the shear web

in (3) gave the sheet loads (2) according to Marguerre's and Cox's formulas. The total load P was then obtained by adding this value to the load carried by the reinforcements

$$P = P_1 + P_2 + P_3 \qquad (5)$$

The resulting load-compression curves A and B (fig. 12) agreed with each other within 2 percent. Further, it is seen that all the measured strains at the stringer centroids were within 13 percent of the calculated strains up to the maximum load of 115,200 pounds, and that the average measured strain at the midsection was within 2 percent of the calculated strains up to a maximum load of 115,200 pounds.

CONCLUSIONS

The following conclusions were drawn from the compressive tests of the monocoque box specimen supplied for this investigation.

1. The loading fixtures were adequate in producing uniform compressive strain over the section of the specimen.

2. The special equipment for measuring stringer strains on a specimen of this type gave consistent and reproducible results.

3. The 0.026-inch sheet between stringers buckled at a stress of about 2,500 pounds per square inch and the 0.075-inch shear web buckled at a stress of about 8,800 pounds per square inch. These values were in agreement with the theoretical buckling stresses for rigid clamping of the sheet at the edges parallel to the load. Permanent set became noticeable at a load of 115,200 pounds; this value corresponded to an average stress in the stringers of about 16,000 pounds per square inch.

4. The measured strain at the stringer centroids near the midsection of the box were within 10 percent of the measured average strains up to the maximum load of 115,200 pounds. The measured average strain at the midsection was within 2 percent of calculated strain at all loads up to the maximum load of 115,200 pounds. The calculated strain was obtained by dividing the load by the product of Young's modulus and effective cross-sectional area, the effective area of the sheet being obtained from Marguerre's formula for a sheet with simply supported edges and from Cox's formula for a sheet with known buckling strain. These formulas had given effective widths in agreement with measured values for the panels described in Technical Note No. 684.

National Bureau of Standards,
Washington, D. C., July 10, 1939.

REFERENCES

1. Ramberg, Walter, McPherson, Albert E., and Levy, Sam: Experimental Study of Deformation and of Effective Width in Axially Loaded Sheet-Stringer Panels. T.N. No. 684, N.A.C.A., 1939.

2. Aitchison, C. S., and Tuckerman, L. B.: The "Pack" Method for Compressive Tests of Thin Specimens of Materials Used in Thin-Wall Structures. T.R. No. 649, N.A.C.A., 1939.

3. Meisse, L. A.: Improvement in the Adaptability of the Tuckerman Strain Gage. A.S.T.M. Proc., vol. 37, pt. II, 1937, pp. 650-654.

4. Timoshenko, S.: Theory of Elastic Stability. McGraw-Hill Book Co., Inc., New York, 1936.

TABLE I. Mechanical Properties of Material

Sample	Young's modulus (lb./sq. in.)		Yield strength (lb./sq. in.) (offset=0.2 percent)		Tensile strength (lb./sq.in.)	Elongation in 2 inches (percent)
	Tension	Compression	Tension	Compression		
Corner angle	10.4×10^6	10.8×10^6	48,000	42,000	61,600	21
Stringer 2	10.4	10.8	48,300	40,700	63,110	25
Stringer 1	10.4	10.8	48,700	40,500	63,100	25
0.075-inch shear web	10.5	10.7	53,700	44,000	70,020	20
0.026-inch top and bottom plating	10.5	10.8	57,100	46,800	73,500	18

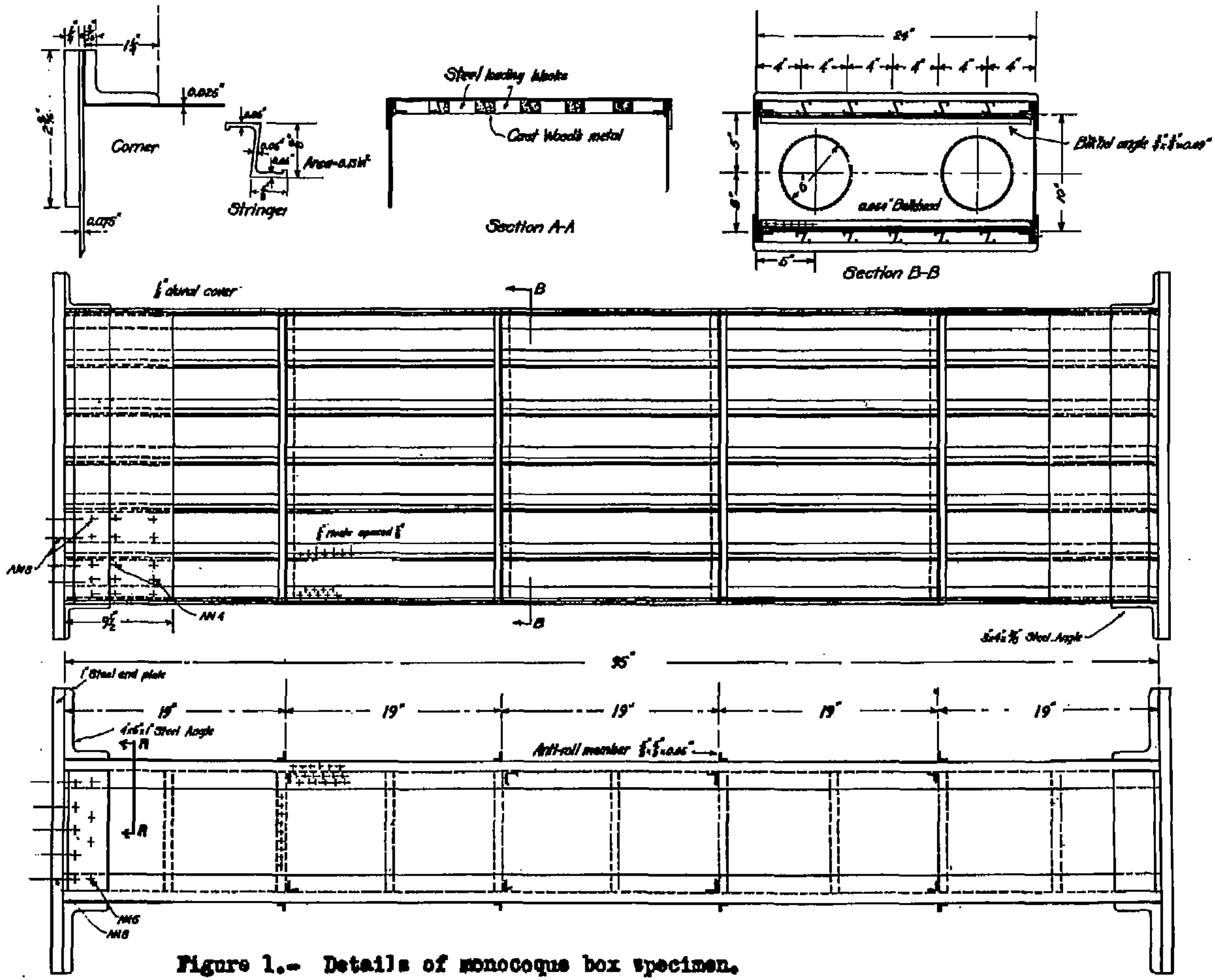

Figure 1.- Details of monocoque box specimen.

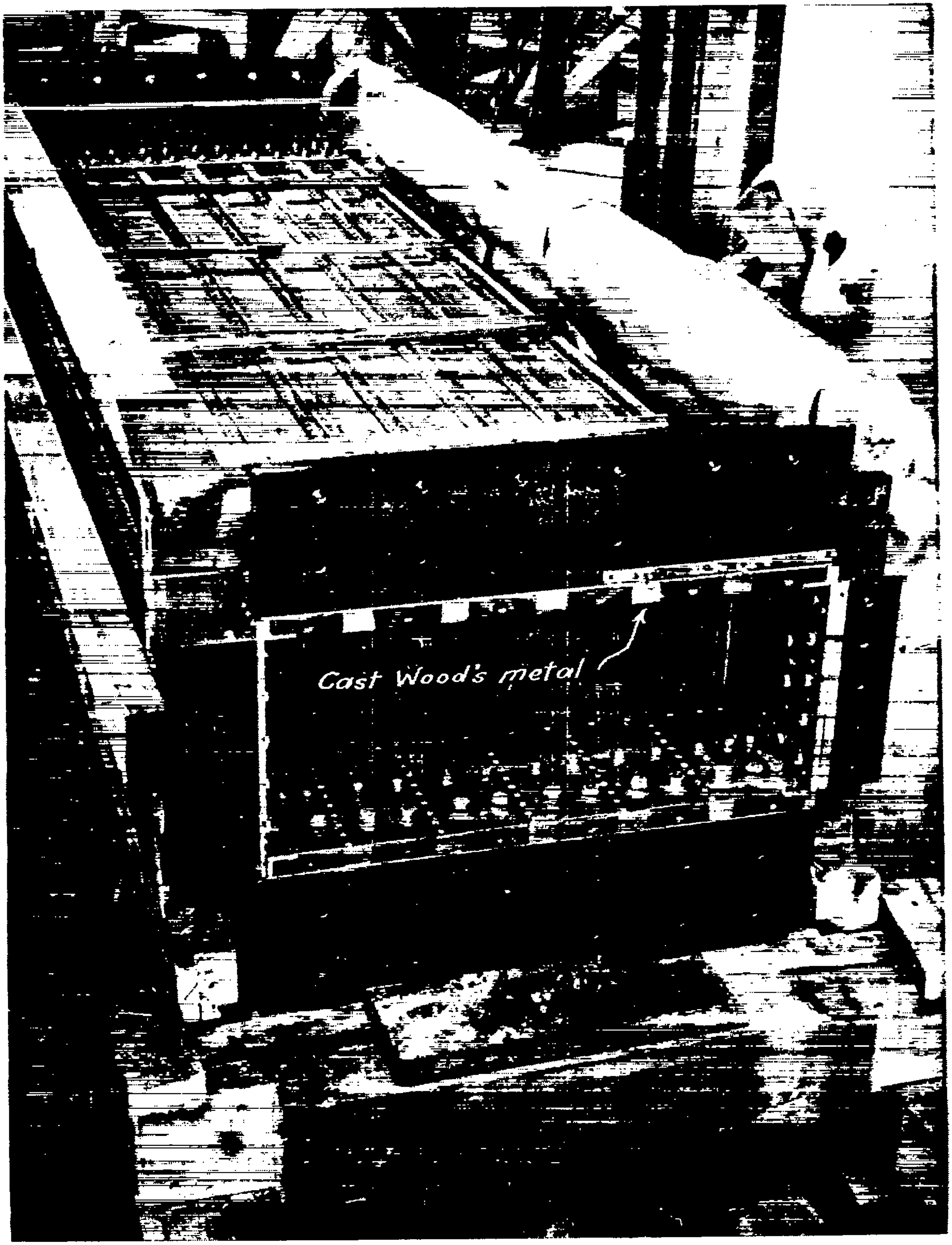

Figure 2.- Over-all view of monocoque box (end plate removed).

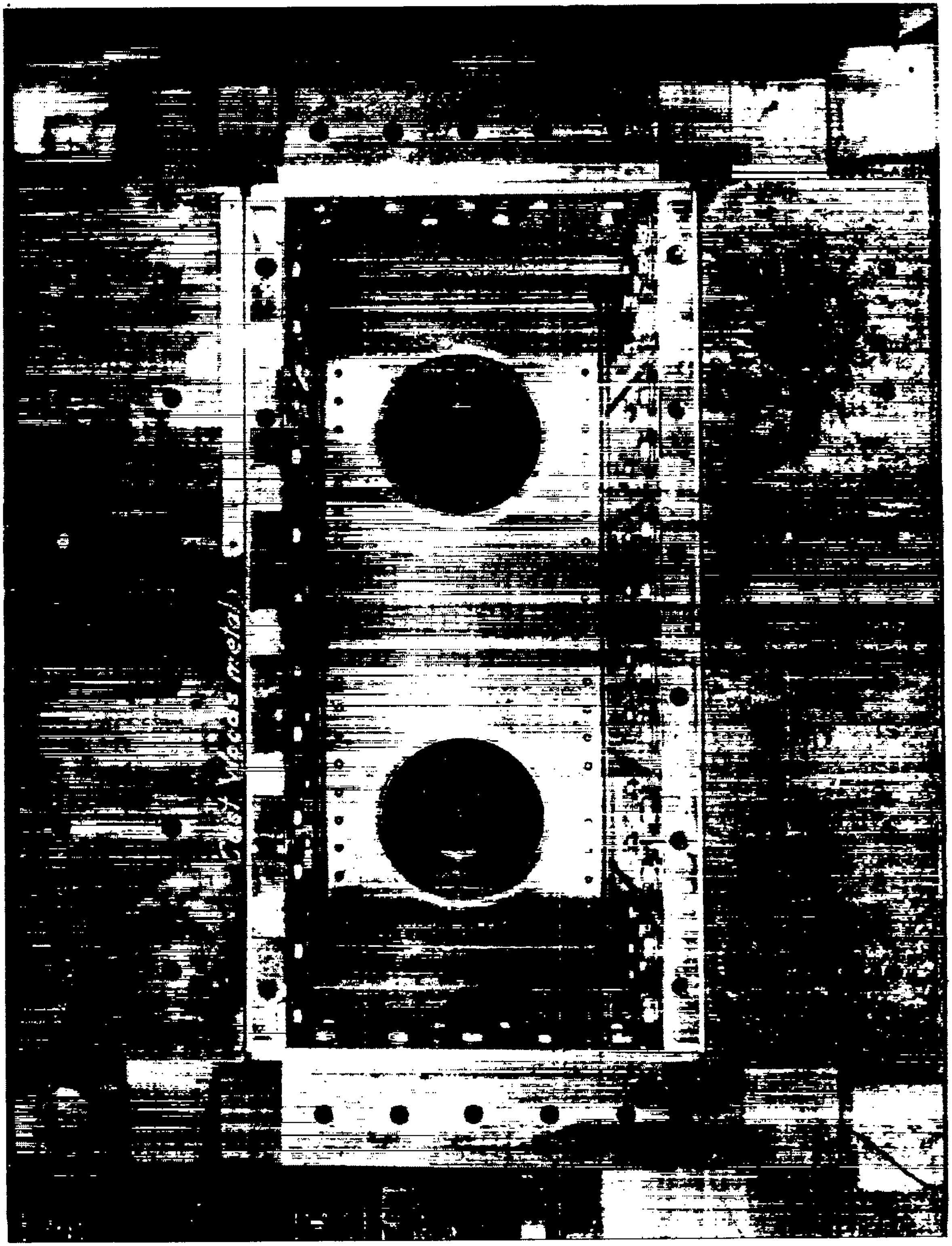

Figure 3.- End view of monocoque box (end plate removed).

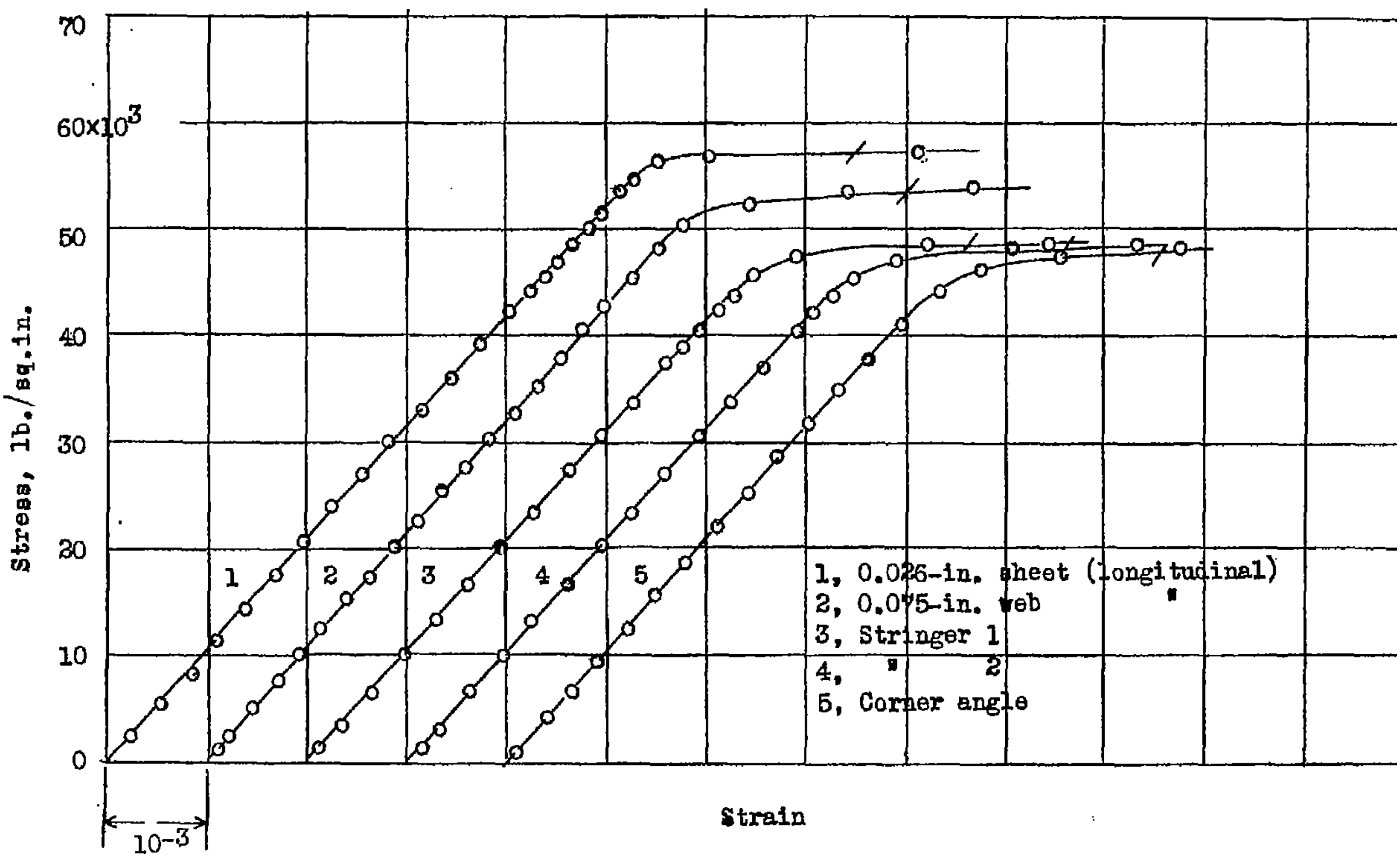

Figure 4.- Tensile stress-strain curves of material.

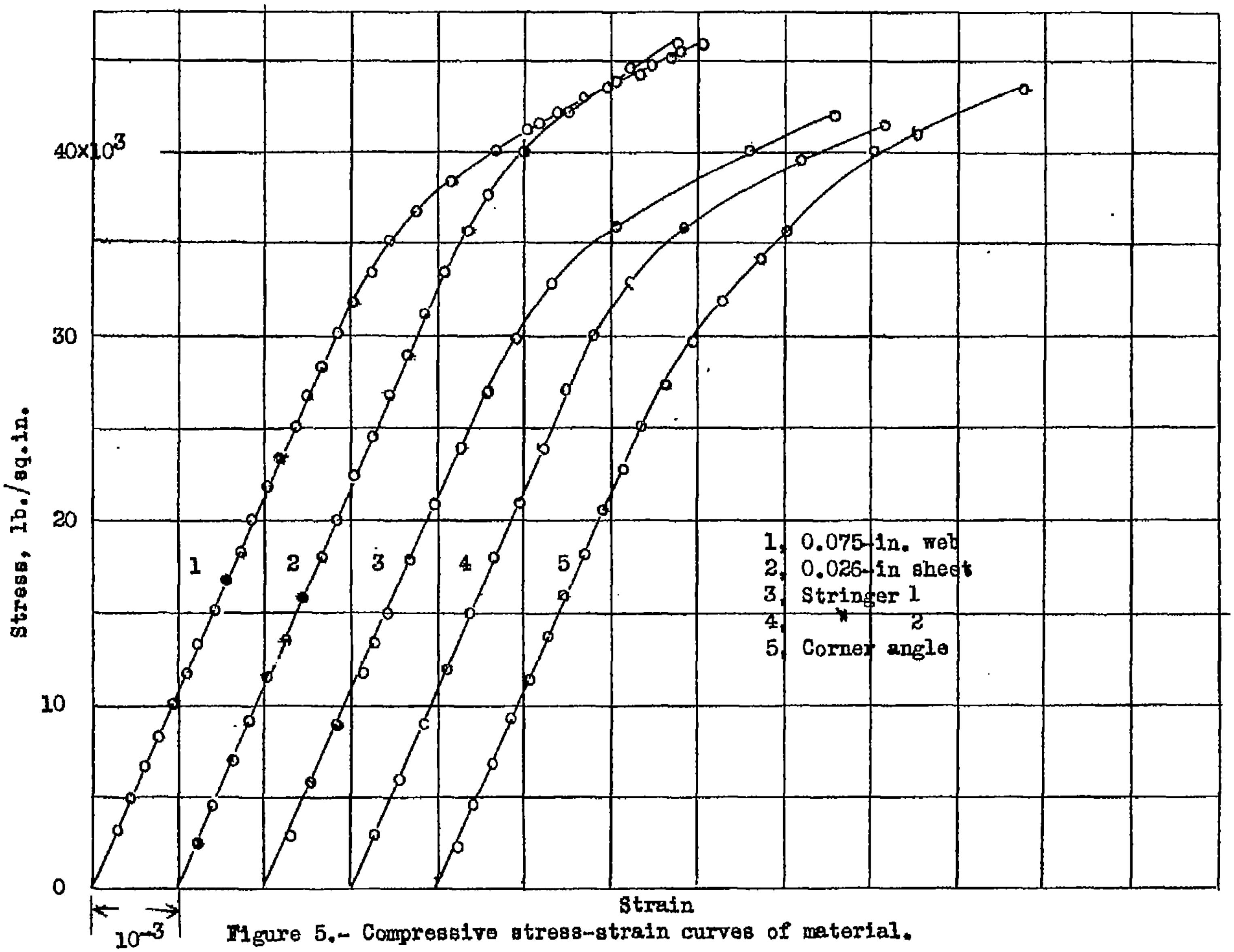

Figure 5.- Compressive stress-strain curves of material.

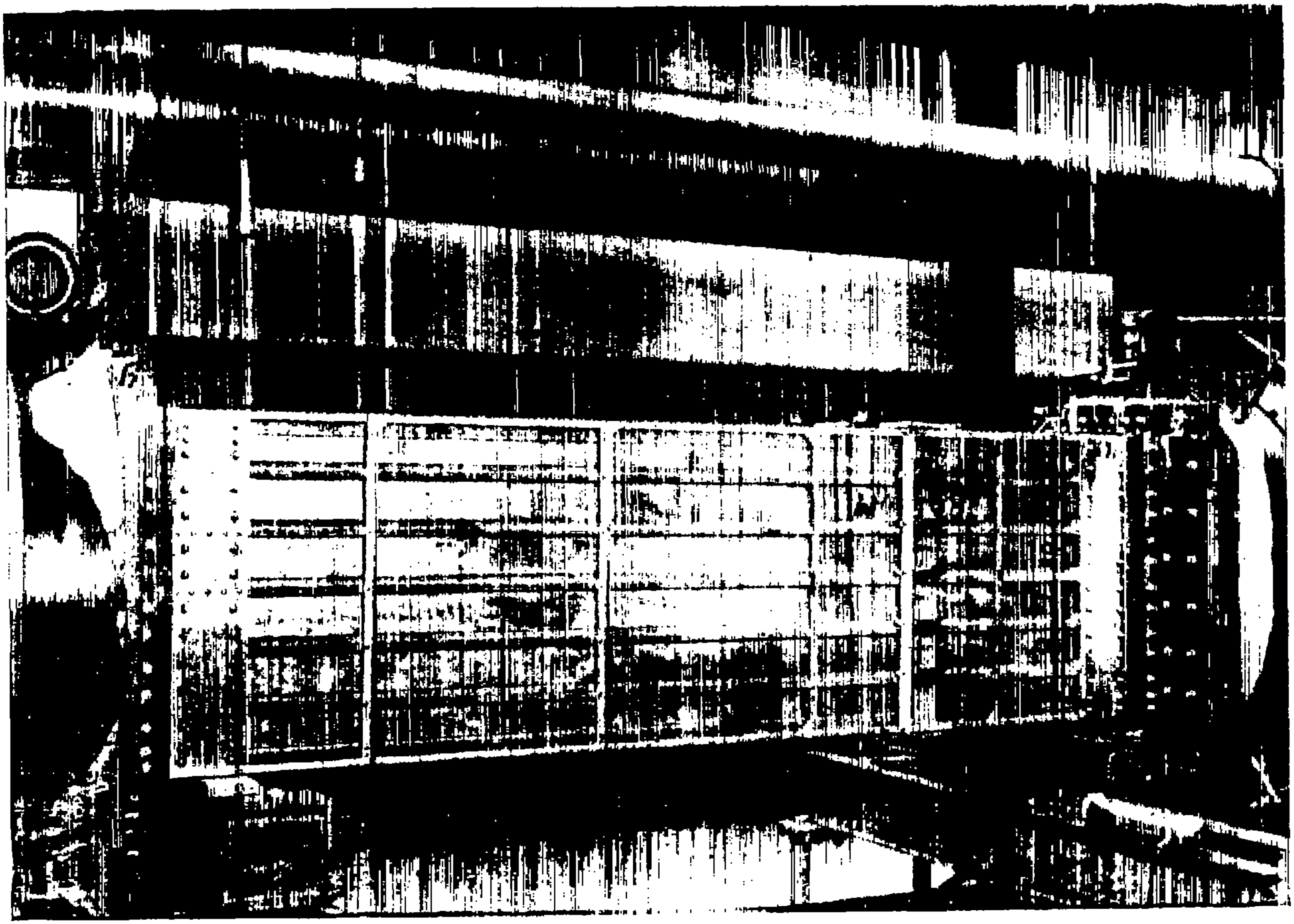

Figure 6.- Monocoque box mounted for compressive test with strain gages near one end.

Fig. 7

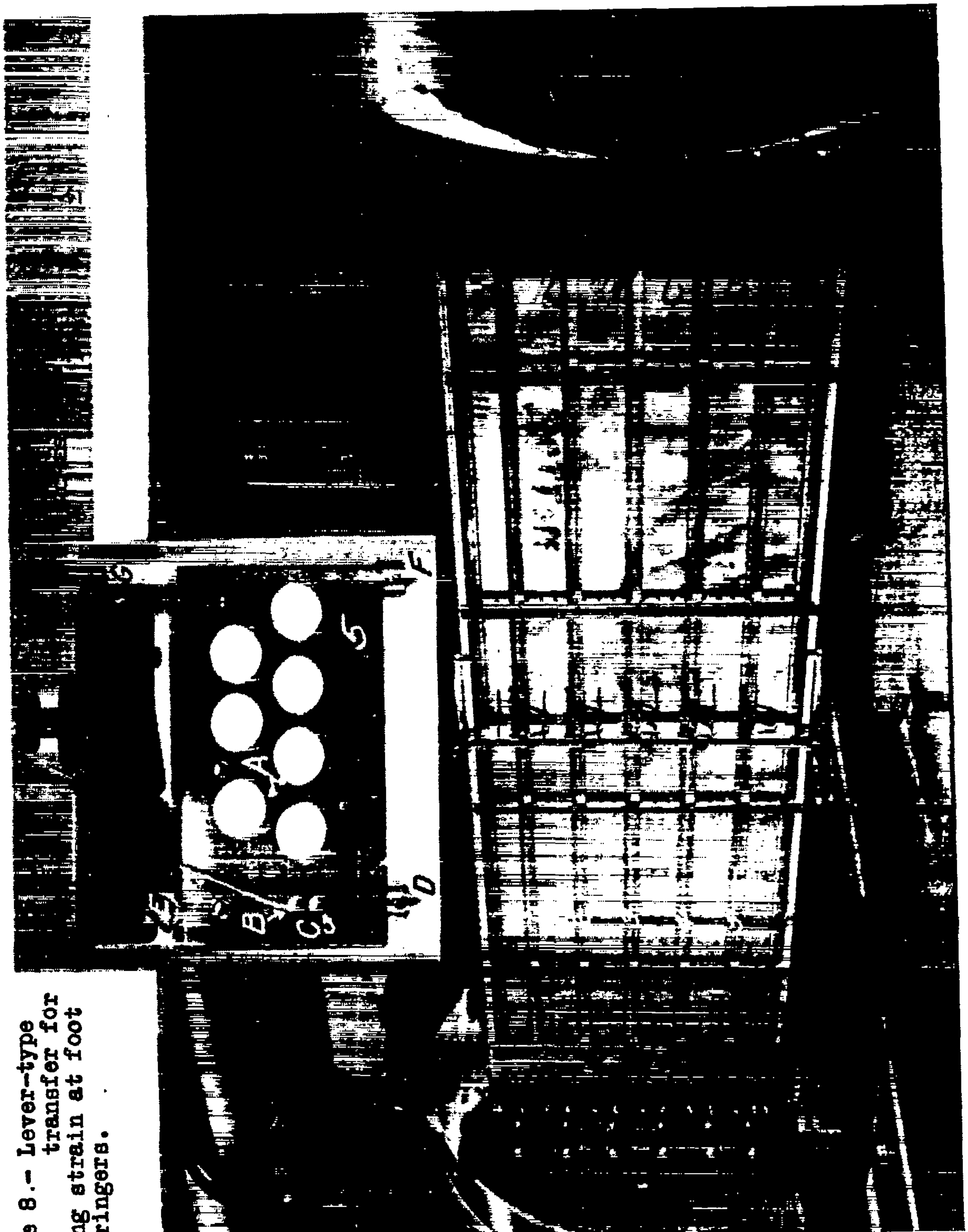

Figure 8.- Lever-type transfer for reading strain at foot of stringers.

Figure 9.- Monocoque box under load of 90,000 pounds showing buckles in sheet.

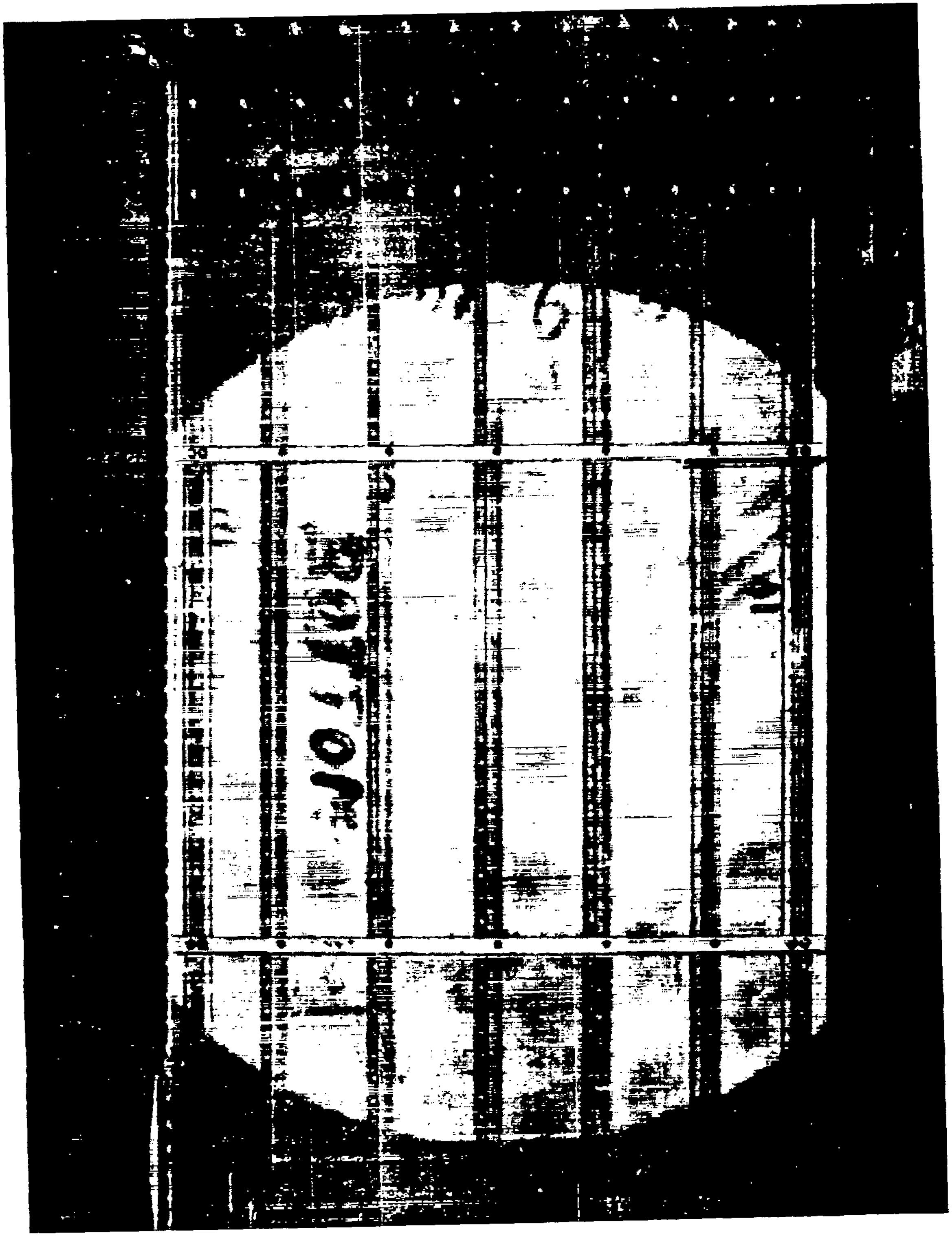

Figure 10.- Close-up of buckles at a load of 90,000 pounds.

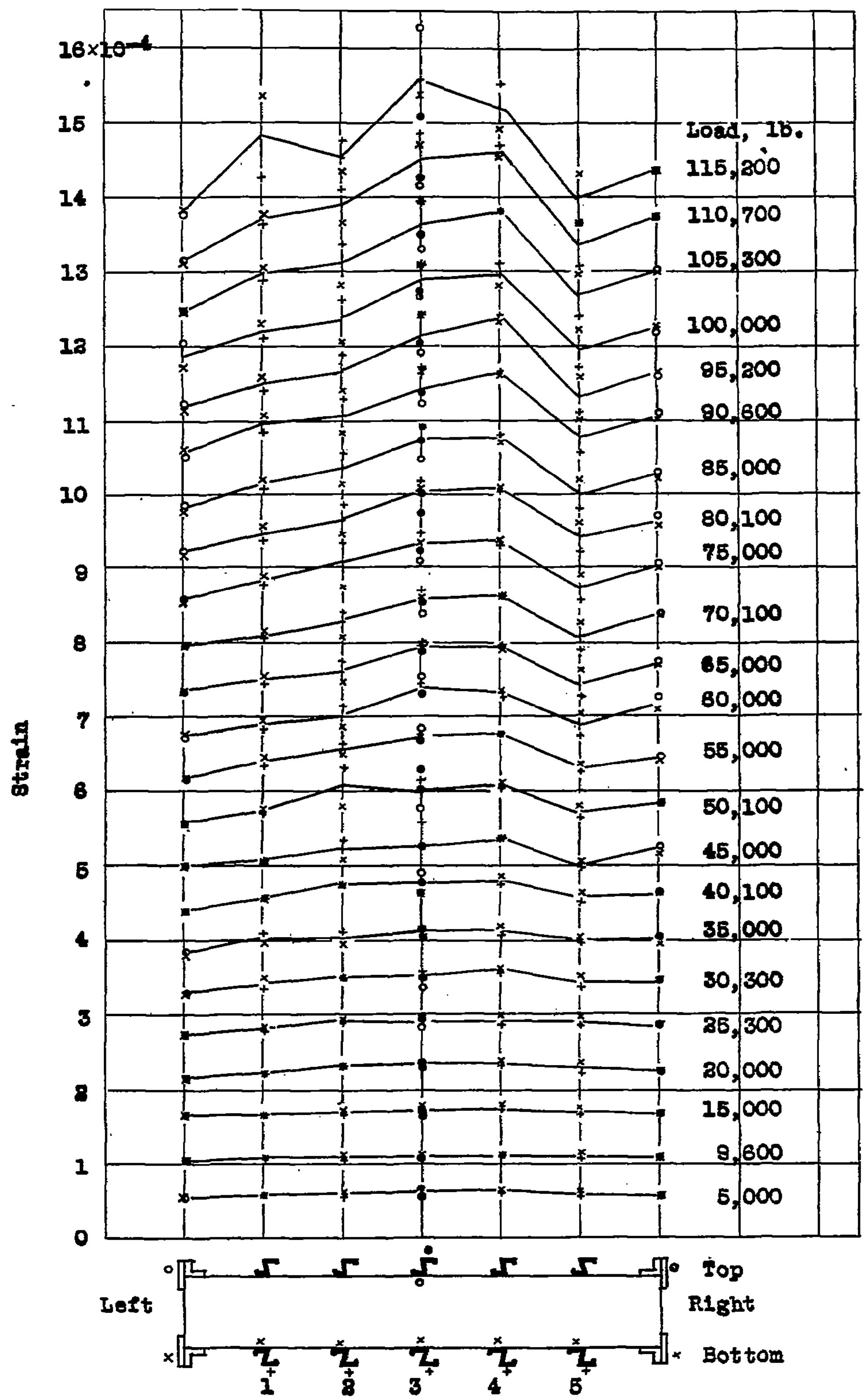

Figure 11.- Strain distribution.

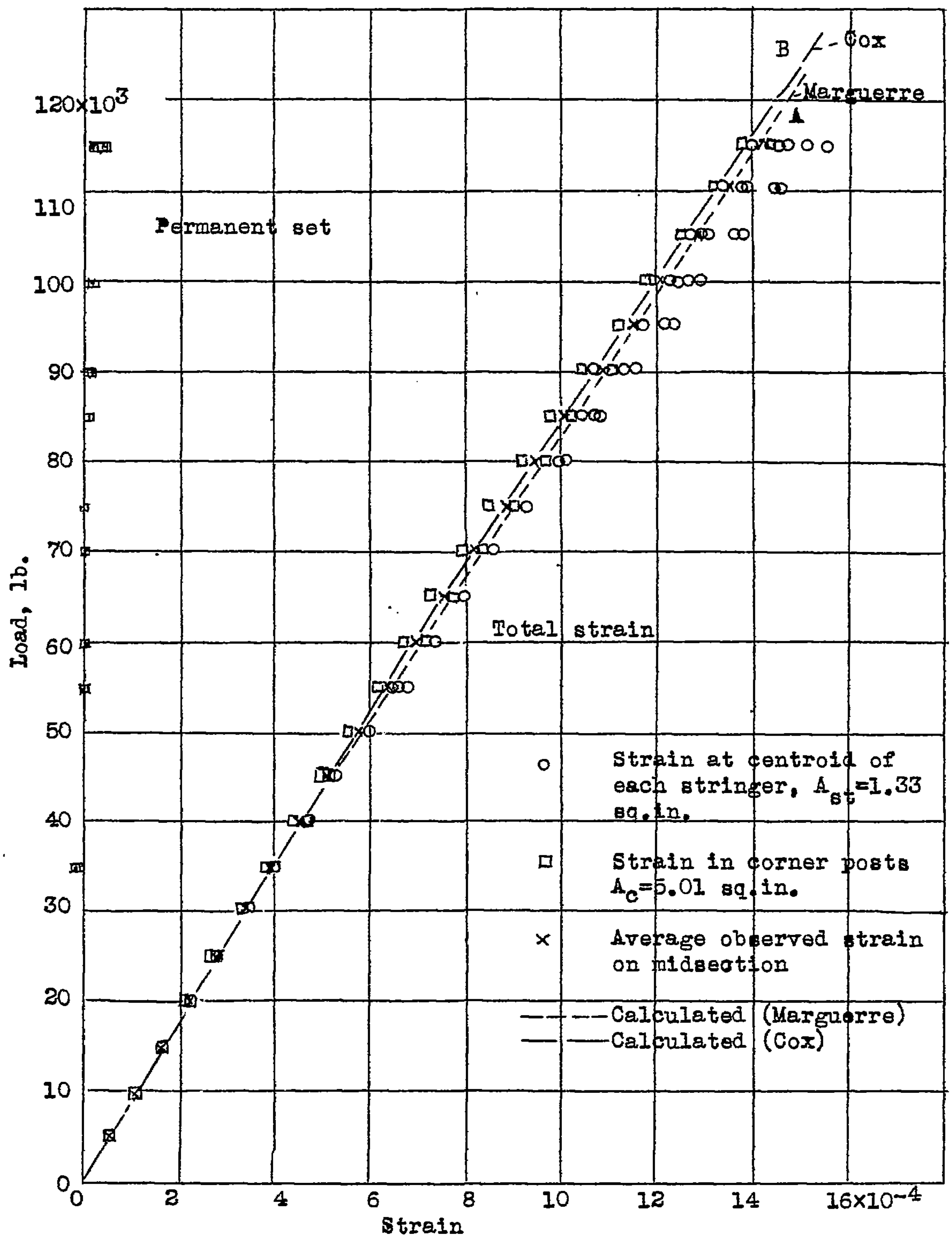

Figure 12.- Comparison of calculated and measured strains.